Requirements Analysis for a Multi-Spacecraft Flight System

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Abstract—The StarLight mission, scheduled to be launched in June 2006, will demonstrate the separated spacecraft technologies of formation flying, precision formation estimation, and long baseline stellar interferometry. The StarLight flight system consists of two spacecraft that will launch as a stacked cluster, separate from each other after a short post-launch checkout, and then operate for at least six months in an Earth-trailing heliocentric orbit. A variety of demonstrations will be performed at inter-spacecraft distances of 30 m to 1000 m.

In order to fully describe the StarLight flight system requirements, we have had to introduce several new dimensions into the typical requirements analysis process. We have used some of these new dimensions to organize our requirements database, in an attempt to create clear distinctions between those requirements that are specific to particular spacecraft, configurations, and/or modes, vs. those requirements that are common to all spacecraft, configurations, and/or modes. This paper will describe our flight system requirements analysis approach, and will also show how a preliminary set of these requirements have been organized within our project requirements database. We believe our approach can be extended to flight systems with larger collections of cooperating spacecraft.

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1. STARLIGHT MISSION INTRODUCTION

The StarLight mission will develop and demonstrate several key technologies that will be used by future constellation missions, particularly separated spacecraft interferometers such as the Terrestrial Planet Finder. Scheduled for launch from Cape Canaveral in June 2006, StarLight will deploy two spacecraft that will operate cooperatively with each other at separations between 30 m and 1000 m. StarLight's technology demonstration objectives include:

(1) autonomous inter-spacecraft range control with an accuracy of 10 cm.

(2) autonomous inter-spacecraft bearing control with an accuracy of 5 arcmin.

(3) measurement of optical-wavelength interference fringes from VM 4 stars at a variety of projected baselines between 30 m and 125 m.

Figure 1 shows the StarLight flight system in its separated configuration.

A single Delta II 7925 launch vehicle will deliver both StarLight spacecraft to an Earth-trailing solar orbit. As shown in Figure 2, the two spacecraft will coast around the Sun together in roughly the same orbit as the Earth, while drifting away from the Earth at a rate of roughly 0.1 AU/year. A solar orbit was chosen over an Earth orbit because it affords a more stable thermal environment, more stable viewing conditions for interferometry, and more stable dynamic conditions for formation flying. For a good introduction to the StarLight mission, its advanced technologies, and its relationship to future mission such as Terrestrial Planet Finder, see References [3], [4], and [5]. For a good introduction to stellar optical interferometry, see References [1] and [2].

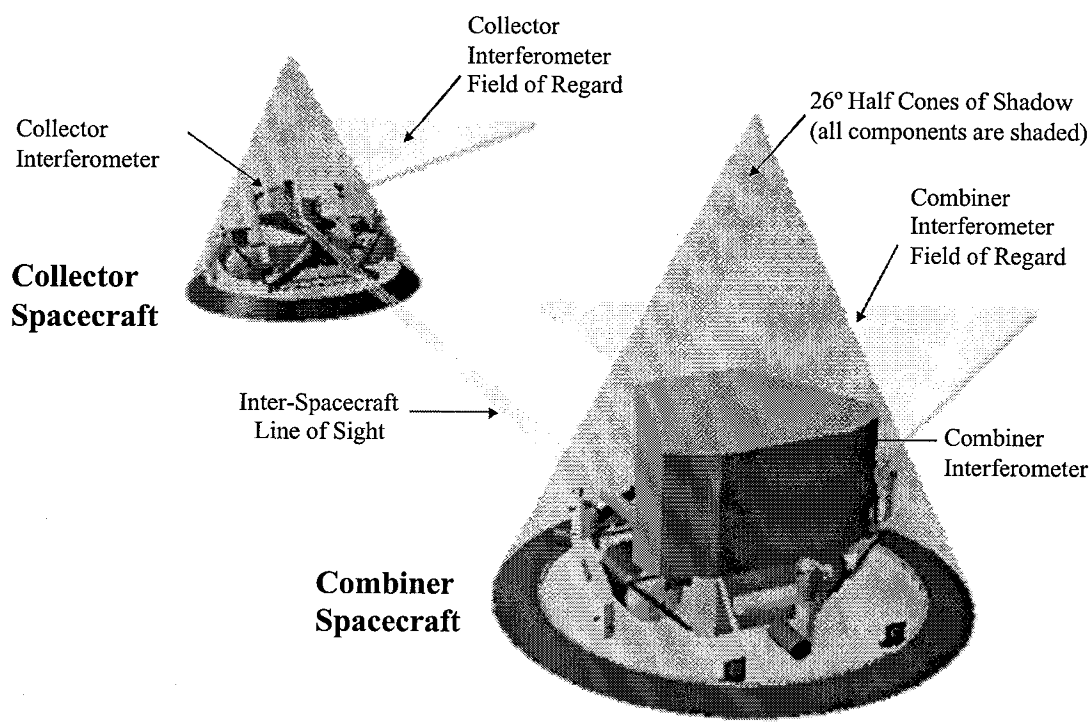

Figure 1. The StarLight Flight System

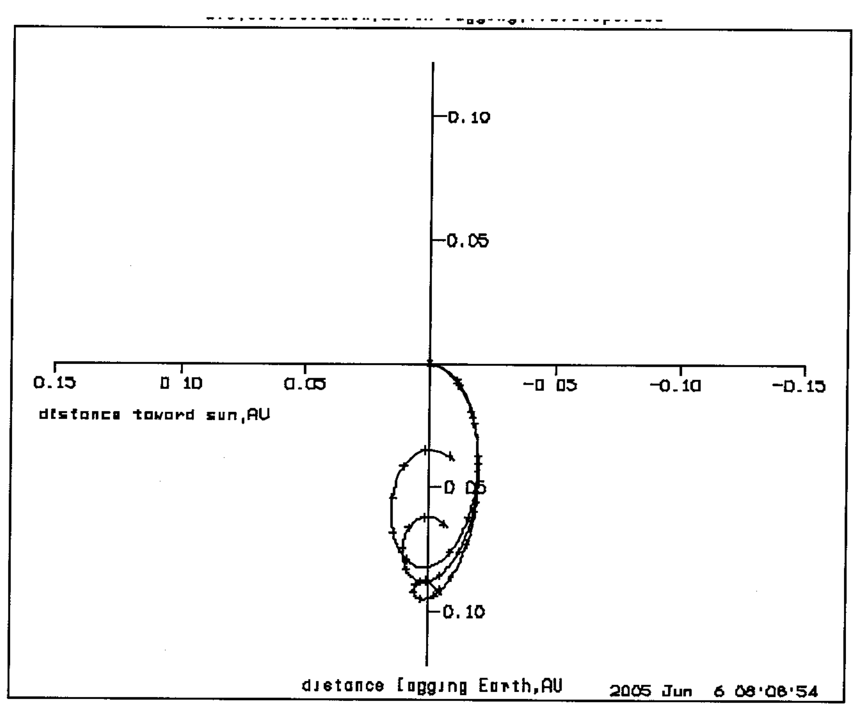

Figure 2. StarLight's Solar Orbit

2. FLIGHT SYSTEM ARCHITECTURE

Figure 3 summarizes the StarLight flight system architecture, illustrating the interactions between the two spacecraft, the information flows within each spacecraft, and the information flows between each spacecraft and the ground system. The three major flight system elements are:

(1) The Two Spacecraft Buses. Each Spacecraft Bus is a self-sufficient system that performs typical space flight engineering functions such as power generation and distribution, thermal control, X-band flight-ground communications, attitude control, translation control, and momentum management. The two Spacecraft Buses also provide an Ultra High Frequency (UHF) inter-spacecraft communications channel that is used to transport both spacecraft and payload data between the two spacecraft. For a more detailed description of the StarLight Spacecraft Buses, see Reference [6].

(2) The Autonomous Formation Flying (AFF) Sensor. The AFF Sensor is a physically distributed payload, with multiple transmitters and receivers on each of the two Spacecraft Buses. It is a fixed-mounted Ka-band system that measures the absolute range and bearing angle between reference points on the two Spacecraft Buses. For a more detailed description of the StarLight AFF Sensor, see Reference [7].

(3) The Interferometer. The Interferometer is a physically distributed payload, with optical and electronics assemblies on each of the two Spacecraft Buses. It precisely measures inter-spacecraft range and bearing changes using an infrared metrology system. It directs starlight from collecting apertures on each spacecraft, into a beam combiner that is located on one of the spacecraft. For a more detailed description of the StarLight Interferometer, see References [8] and [9].

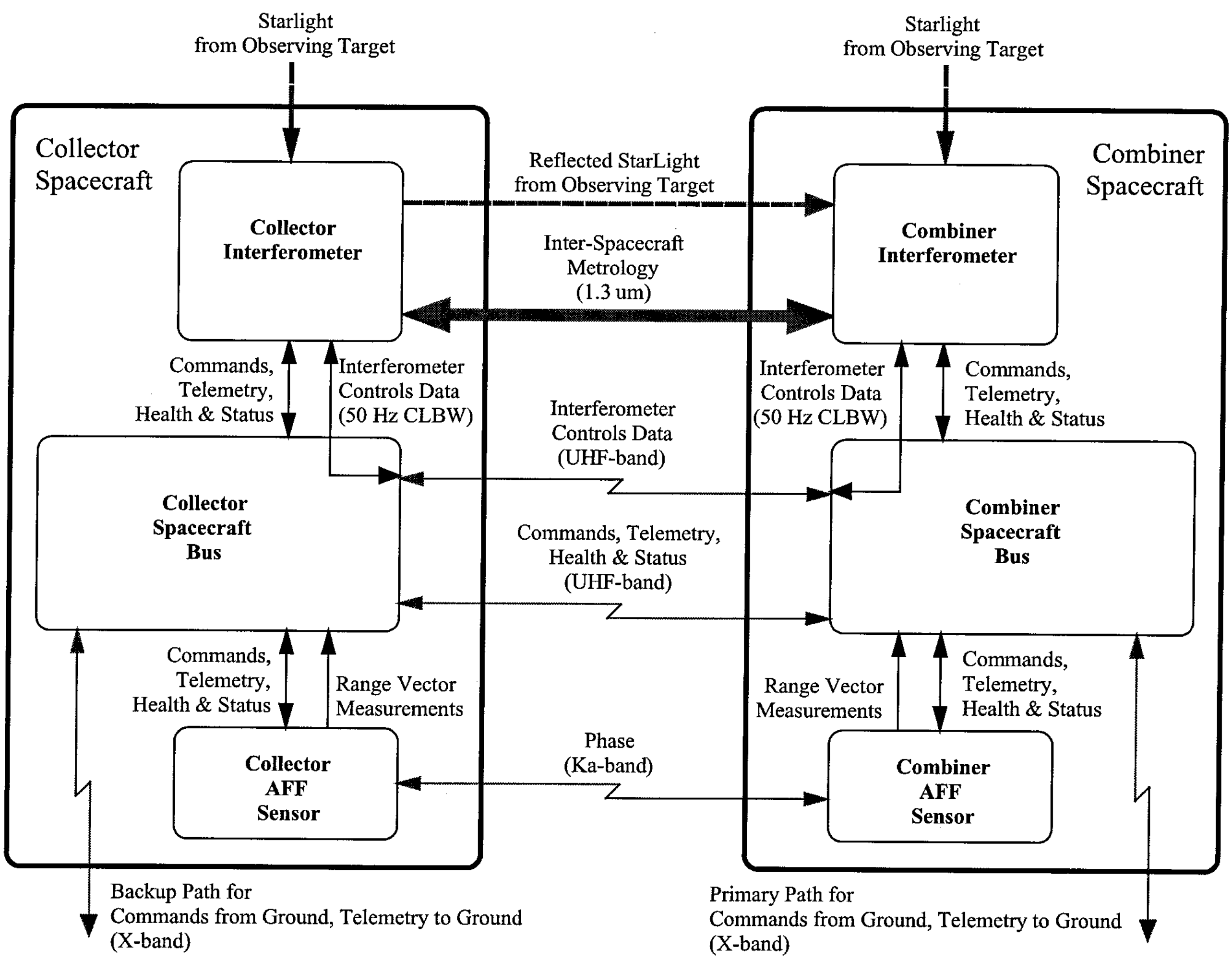

Figure 3. Functional Block Diagram for the StarLight Flight System

As shown in Figure 3, the two halves of the flight system are termed the Combiner Spacecraft and the Collector Spacecraft. The Combiner Spacecraft, so named because it hosts the Interferometer's beam combiner, consists of the Combiner Spacecraft Bus and its physically resident payload systems, the Combiner AFF Sensor and the Combiner Interferometer. Similarly, the Collector Spacecraft consists of the Collector Spacecraft Bus and its physically resident payload systems, the Collector AFF Sensor and the Collector Interferometer.

The Combiner and Collector Spacecraft have many common characteristics, but they are not identical. The two spacecraft buses have similar dimensions, similar maneuvering capabilities, and identical computing resources. The AFF Sensor provides identical hardware and software to each spacecraft. However, the Interferometer's hardware and software capabilities are primarily resident on the Combiner Spacecraft. This asymmetry motivates differences in the two spacecraft's sunshade configurations, their solar array layouts, and their flight-ground communications capabilities. Since the two spacecraft launch in a stacked configuration, this motivates differences in their load-bearing structure; furthermore, the Collector Spacecraft is unique in its accommodation of the launch vehicle adapter.

Each spacecraft stands less than 2 meters tall and has a maximum diameter of roughly 2.7 meters. The total flight system launch mass of approximately 800 kg includes almost 100 kg of gaseous nitrogen (50 kg on each spacecraft), which will be used primarily for ground-directed repositioning of the two spacecraft with respect to each other.

Each spacecraft bus is predominantly a single-string system, with some sparse functional and/or physical redundancy. Since each spacecraft has flight-ground communications capability, failure of that capability on one spacecraft would not be mission catastrophic. Each of the payload systems is also single-string. Failure of either the Combiner AFF Sensor or the Collector AFF Sensor would cause a complete loss of the flight system's formation flying capability. Failure of the Combiner Interferometer would cause a complete loss of the flight system's interferometry capability. Failure of the Collector Interferometer would cause a loss of separated spacecraft interferometry, leaving intact a 1 m baseline interferometry capability within the Combiner Interferometer.

It is important to note that all of the Flight System's technology demonstrations will require a high degree of interaction between the three flight system elements. The Interferometer cannot acquire inter-spacecraft metrology and starlight without precise formation control from the Spacecraft Buses. However, the Spacecraft Buses cannot control the formation without periodic range and bearing measurements from the AFF Sensor. Completing a circle of dependencies, some of the AFF Sensor calibrations will require measurements from the Interferometer's inter-spacecraft metrology system. These performance dependencies elevate the importance of complete and accurate interface requirements between the flight system elements.

3. Mission Operations Overview

Figure 4 is a high-level summary of the StarLight mission timeline. StarLight's mission will consist of a six-month primary mission and a six-month extended mission.

StarLight will accomplish all of its mission success criteria during its primary mission. During this entire phase, the Starlight Flight System will be operated as a ground-directed "flying test bed", with the Deep Space Network providing tracking and two-way communications capability for at least 8 hours per day, normally during the prime shift for the JPL-centered operations team.

Technology demonstration will begin a few days after launch, when the ground will direct the two spacecraft to separate from each other and initiate autonomous cooperative formation flying using the uncalibrated AFF Sensor System. During the next six to ten weeks, the flight system will execute a variety of ground-directed formation maneuvers, in order to characterize the AFF Sensor System performance at a variety of ranges and orientations. During this period, the ground will also direct checkouts and alignments of the Combiner-resident portion of the Interferometer.

Within ten weeks of launch, the flight system will have inter-spacecraft bearing knowledge at the 5 arcmin level, which will be good enough to support the initial acquisition of inter-spacecraft metrology by the Interferometer at a range of 30 m. Subsequent ground-directed alignment activities will improve the inter-spacecraft bearing knowledge to the 1 arcmin level, and will also enable the relay of starlight from the collecting optics on the Collector Spacecraft to the beam combiner on the Combiner Spacecraft. The first separated spacecraft interference fringe is expected within four months of launch, at a range of 30 m.

The acquisition of interference fringes at 30 m will permit additional calibration and alignment of the entire flight system, enabling subsequent acquisition of interference fringes at larger ranges. Fringe acquisition at a range of 600 m (a projected baseline of 125 m) is expected by the end of the primary mission.

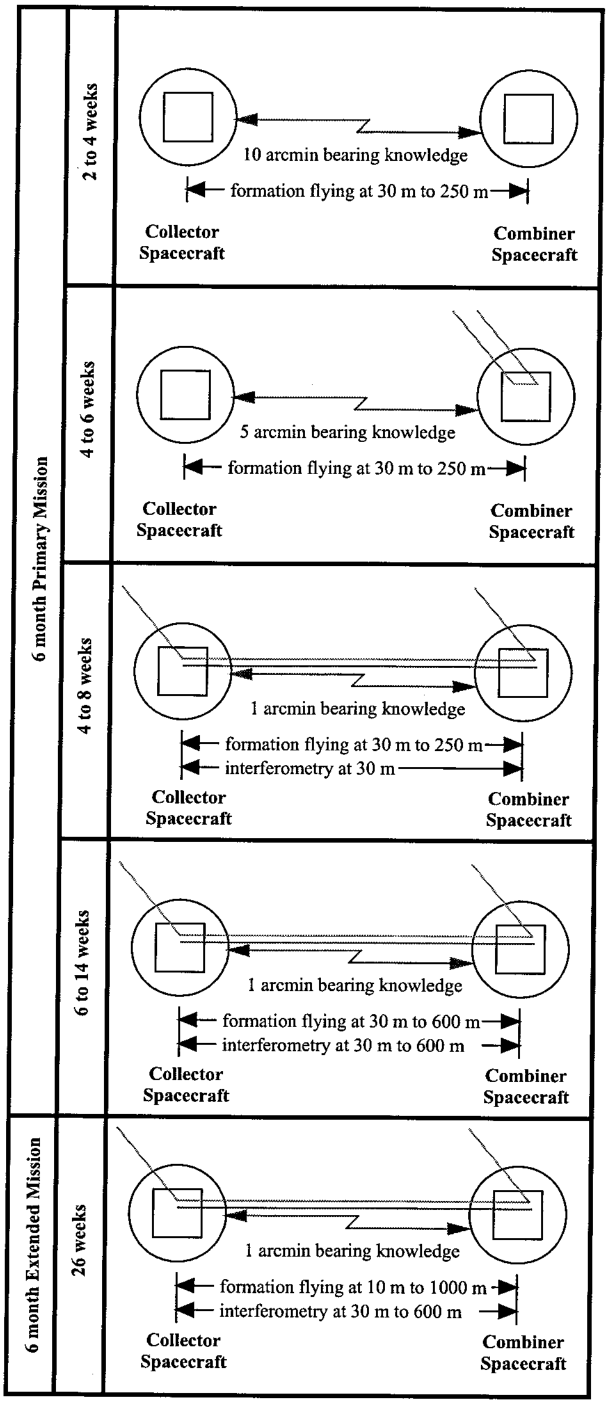

Figure 4. StarLight Mission Timeline

The six-month extended mission will be used to repeatedly observe some of the primary mission stars, and also to observe additional stars. This will provide some characterization of the Interferometer's measurement repeatability, range sensitivity, and source brightness sensitivity. During the extended mission, the flight system will also perform additional ground-directed formation flying demonstrations, including the application of different optimal control criteria, and long baseline demonstrations (perhaps out to 1 km).

During all of the planned mission activities, StarLight's two spacecraft will be expected to operate cooperatively, with one of the spacecraft handling all the flight-ground communication. During cooperative operation, the two spacecraft must negotiate mastership of several flight system engineering functions, including timekeeping, telemetry storage, and formation control. The two spacecraft must also be capable of standalone operation during ground testing, and they must be able to transition to standalone operation if necessary following in-flight anomalies.

Figure 5 illustrates StarLight's observing geometry for separated spacecraft interferometry. The Combiner

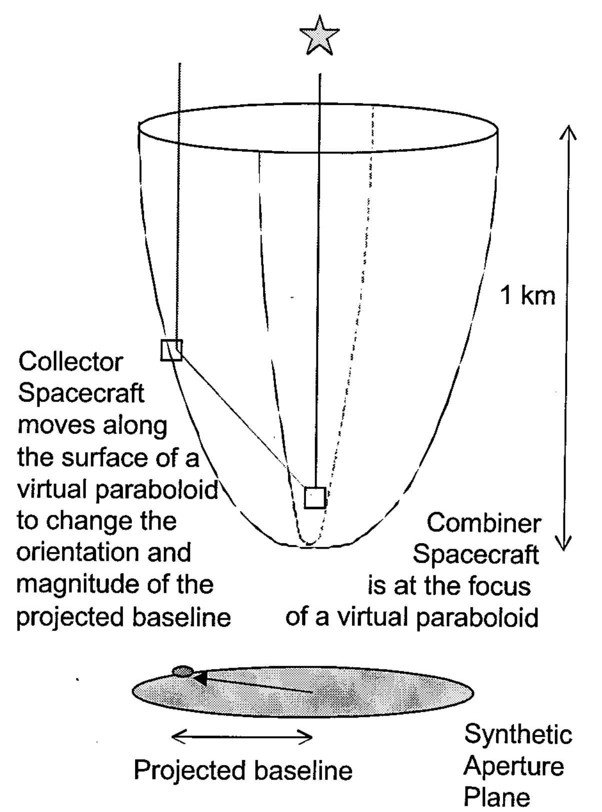

Figure 5. StarLight Observing Geometry

Spacecraft sits at the focus of a very narrow virtual paraboloid. The Collector Spacecraft moves along the surface of that paraboloid, always facing the Combiner Spacecraft, so that it can relay starlight in that direction. A fixed delay line in the Combiner Interferometer compensates the 10 m difference between the direct starlight path and the indirect starlight path. For more information on this observing geometry and its implications on the StarLight Interferometer design, see Reference [9]. The main point here is that the Flight System can fill the synthetic aperture plane by changing the projected baseline's magnitude and/or its orientation with respect to the target star. Since power and straylight considerations prevent the Interferometer from being pointed within 70 degrees of the Sun, complete aperture filling will only be possible for targets near the ecliptic poles. Targets near the ecliptic plane will only be viewable every six months, for periods of approximately 40 days.

4. THE FLIGHT SYSTEM REQUIREMENTS ANALYSIS CHALLENGE

Figure 6 illustrates the flow of Starlight's Project-level requirements to the StarLight Flight System.

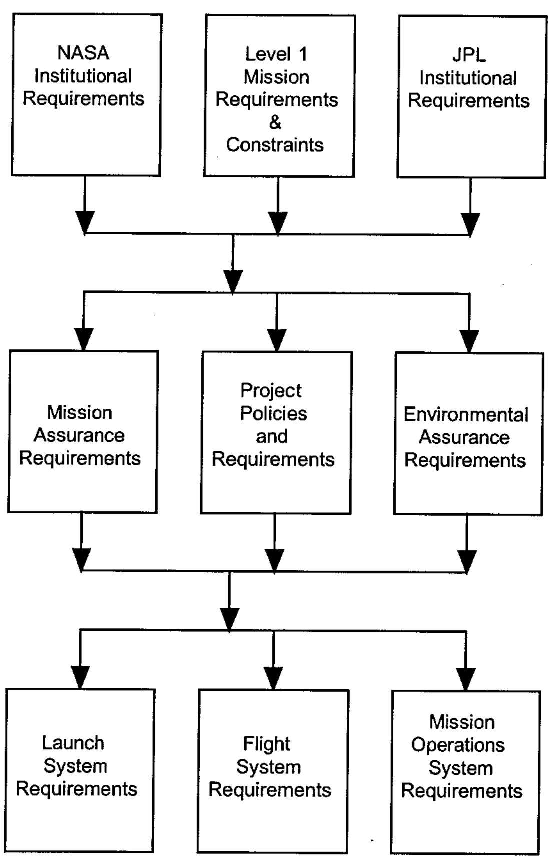

Figure 6. StarLight Project Requirements Flow

The Flight System is one of three Project-level systems, the others being the Mission Operations System (MOS) and the Launch System.

Functional and performance requirements flow to the Flight System from the Project Policies and Requirements Document (PPRD). The PPRD also captures the Flight System's high-level requirements for interfacing to the MOS and the Launch System. Analysis, design, and construction standards flow to the Flight System from the Mission Assurance Requirements Document (MARD). Environmental design and test requirements flow to the Flight System from the Environmental Assurance Requirements Document (EARD). This requirements flow is fairly typical of recent JPL flight projects, and most of the Project-level requirements are unconditional statements of the form "The Flight System shall.....". Wherever possible, the Project-level requirements obscure the fact that the StarLight Flight System is composed of multiple spacecraft, acting cooperatively with each other and carrying distributed payloads. This is good practice, since it maximizes the freedom of the Flight System developers in meeting the Project-level requirements.

Given the Project-level requirements described above, the Flight System architecture described in Section 2, and the Mission Operations concept described in Section 3, the Flight System requirements analysis challenge is summarized in Figure 7. This figure identifies the many dimensions of assignment and conditioning that must be considered in order to translate each Project-identified capability or constraint into a full description of the corresponding Flight System requirement(s).

Some of these analysis dimensions (e.g. the allocation of a Project requirement to a particular Flight System element) are typical of any Flight System. However, several of these analysis dimensions are uniquely necessary because the StarLight Flight System consists of two spacecraft with distributed payloads, acting cooperatively. These additional dimensions, which would be relevant to any multiple-spacecraft flight system, include:

- Flight System Sub-Element
- Flight System Configuration
- Flight System Operational Mode
- Flight System Orientation
- Flight System Operating Range
- Flight System Performance Level

The following sub-sections describe these analysis dimensions in more detail, along with the StarLight-specific enumeration of each dimension.

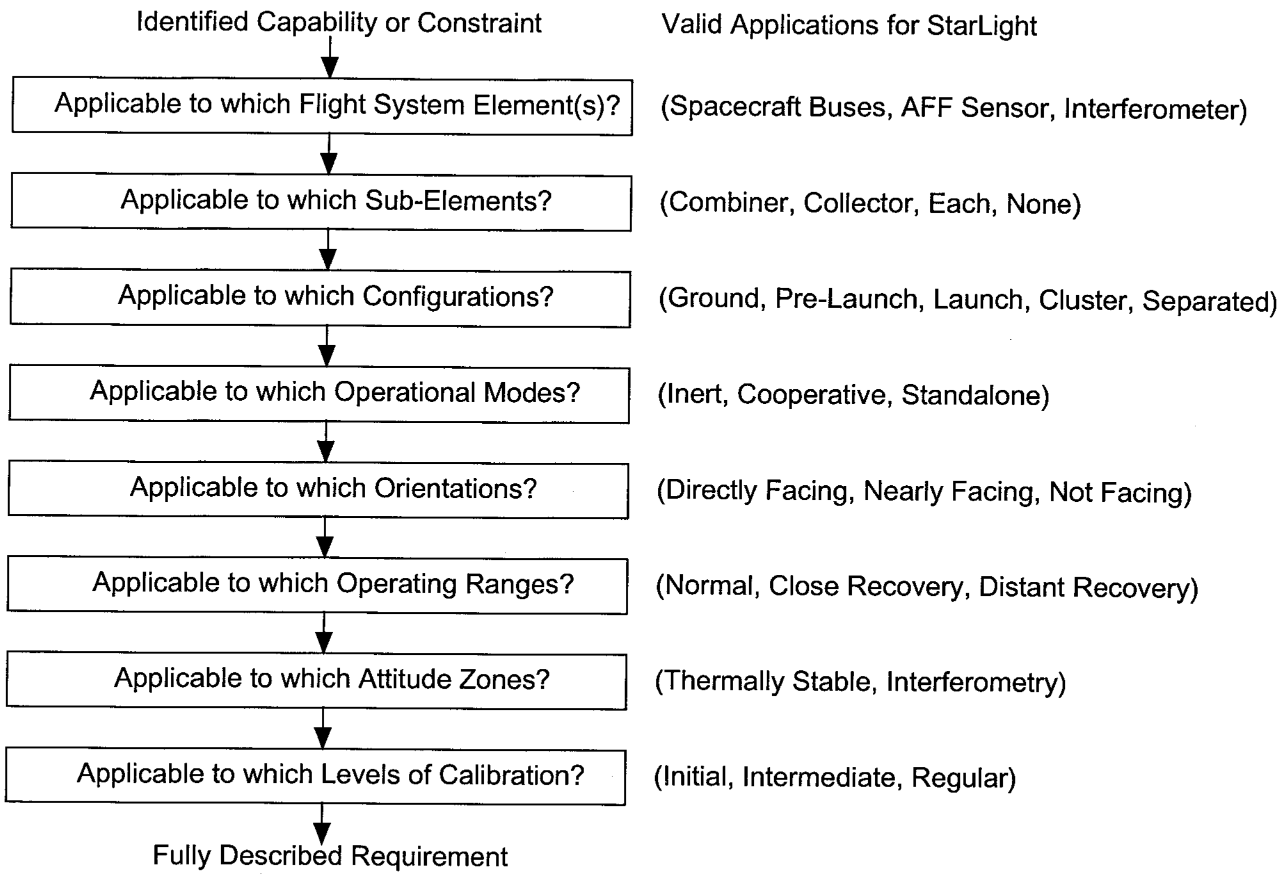

Figure 7. Requirements Analysis for the StarLight Flight System

Flight System Sub-Element

Since each of the three flight system elements has physically separable sub-elements (i.e. the Combiner and Collector portions), each relevant requirement for that system element must be clearly assigned to one or both sub-elements. Valid StarLight sub-element assignments are:

(1) **No sub-element assignment**, in which the requirement is to be satisfied collectively by the Combiner and Collector portions of the system. Further decomposition of this requirement between the sub-elements is permitted (but not required) at the system element level. Many of the AFF Sensor's performance requirements (e.g. range knowledge accuracy) are of this type.

(2) **Common sub-element assignment**, in which the requirement is to be satisfied by each sub-element, independent of the other sub-element. Many environmental requirements (e.g. total ionizing dose) are of this type.

(3) **Specified sub-element assignment**, in which the requirement is to be satisfied by a specified sub-element, without any assistance from the other sub-element. Such a requirement is not applicable for the other sub-element. The Combiner Interferometer has many requirements (e.g. unique fields of regard) of this type.

Note that the sub-element dimension is distinct from the subsystem dimension, which is traditionally used for requirements allocation within a flight system element. Whereas the subsystem dimension is transparent at the flight system level, the sub-element dimension is an important flight system dimension, since it facilitates interface definition between the flight system elements. Sub-elements may or may not host identical subsystems, and a subsystem can span multiple sub-elements. For example, the Interferometer's metrology subsystem has assemblies in both the Combiner Interferometer and the Collector Interferometer.

Flight System Configuration

The two spacecraft will be tested and operated in several different configurations, which capture significant differences in their physical arrangement and their external interfaces. These flight system configurations, illustrated in Figure 8, are listed below in a rough chronology:

(1) The **unstacked ground configuration**, in which the Flight System is directly attached to its ground support equipment, the Flight System is not attached to the launch vehicle, and the Flight System's two spacecraft are not attached to each other.

(2) The **stacked ground configuration**, in which the Flight System is directly attached to its ground support equipment, the Flight System is not attached to the launch vehicle, and the Flight System's two spacecraft are attached to each other.

(3) The **pre-launch configuration**, in which the Flight System is directly attached to its ground support equipment, the Flight System is attached to the launch vehicle, and the Flight System's two spacecraft are attached to each other.

(4) The **launch configuration**, in which the Flight System is no longer attached to its ground support equipment, the Flight System is attached to the launch vehicle, and the Flight System's two spacecraft are attached to each other.

(5) The **cluster configuration**, in which the Flight System is no longer attached to the launch vehicle or its ground support equipment, and the Flight System's two spacecraft are attached to each other.

(6) The **separated configuration**, in which the Flight System is no longer attached to the launch vehicle or its ground support equipment, and the Flight System's two spacecraft are separated from each other.

Each flight system requirement, and each subsequent allocation to a flight system element, must be clearly identified as applicable to all configurations, or applicable to a particular subset of these configurations. On StarLight, our two largest sets of requirements are those that are applicable to all configurations (e.g. accept ground commands), and those that are only applicable to the separated configuration (e.g. measure interference fringes on VM 4 stars).

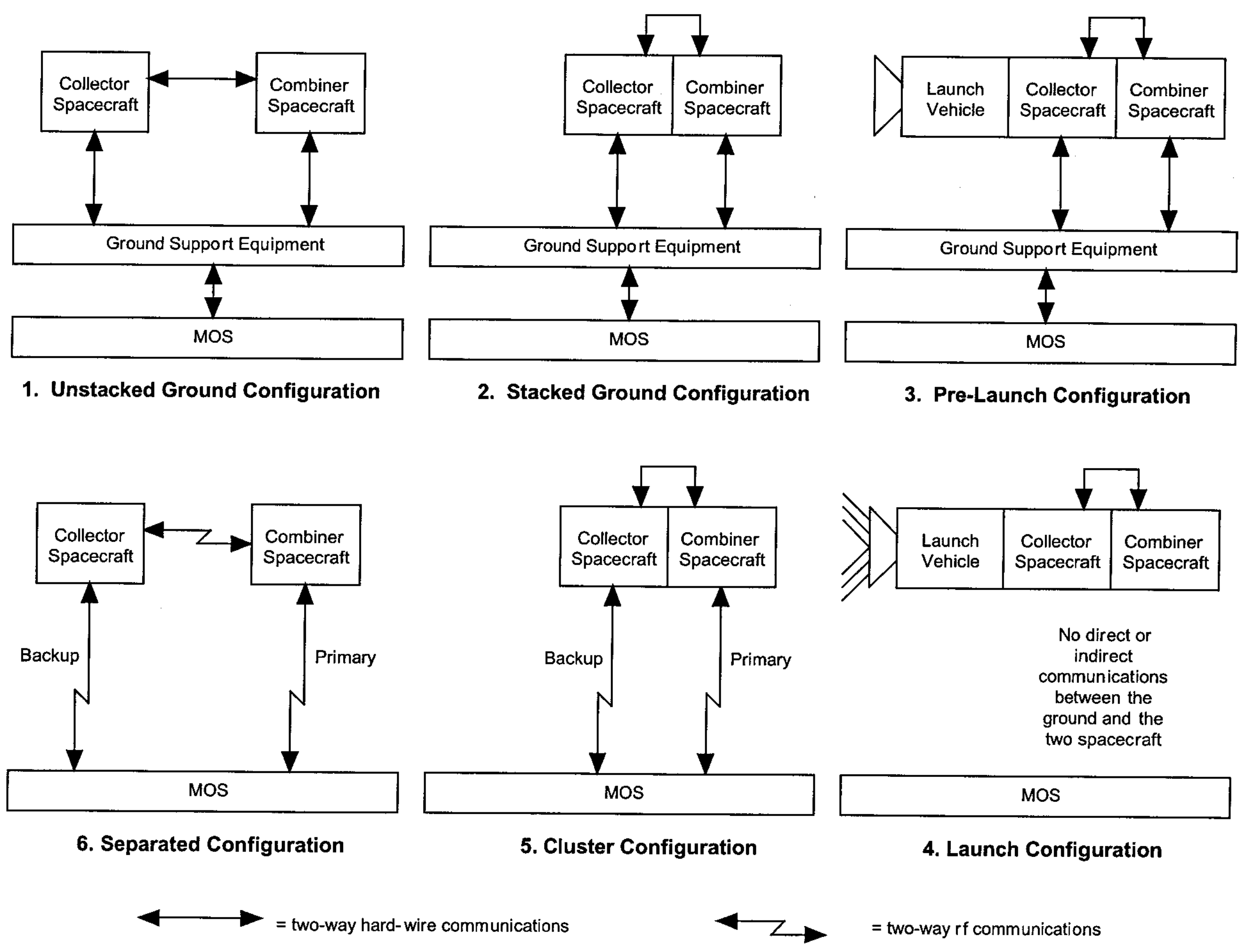

Figure 8. StarLight Flight System Configurations

Flight System Operational Mode

The two spacecraft will be tested and operated in different operational modes, which capture significant differences in their interactional behavior. These flight system operational modes are:

(1) The **inert mode**, in which neither of the two spacecraft is powered and responsive to the MOS.

(2) The **standalone mode**, in which either or both of the two spacecraft are powered and responsive to the MOS, and each spacecraft is acting independently of the other spacecraft, as the master of its own tasks.

(3) The **cooperative mode**, in which both spacecraft are powered and responsive to the MOS, and are capable of working together on shared tasks in prescribed master/slave roles.

Each flight system requirement, and each subsequent allocation to a flight system element, must be clearly identified as applicable to all operational modes, or applicable to a particular operational mode. For StarLight, all the driving requirements are those that are particular to cooperative mode.

Flight System Orientation

The two spacecraft will be operated and tested at a variety of orientations, which have been grouped into three domains for the purpose of requirements specification. These three flight system orientations, illustrated in Figure 9, are:

(1) The **directly facing orientation**, in which the AFF bearing angle (i.e. the angle between the range vector and the AFF sensor boresight) on each spacecraft is less than 2 degrees. This is the only orientation in which the Flight System can do formation mode interferometry., and thus it is the only orientation for which the AFF Sensor will be specifically calibrated.

(2) The **nearly facing orientation,** in which the AFF bearing angle on one or both spacecraft is greater than 2 degrees, and the AFF bearing angle on each spacecraft is less than 45 degrees. The Flight System will commonly transition to this orientation for extended periods of time during formation change maneuvers.

(3) The **not facing orientation**, in which the AFF bearing angle on one or both spacecraft is greater than 45 degrees. This orientation has no planned use during normal operations, but the Flight System could enter this orientation following several types of anomalies.

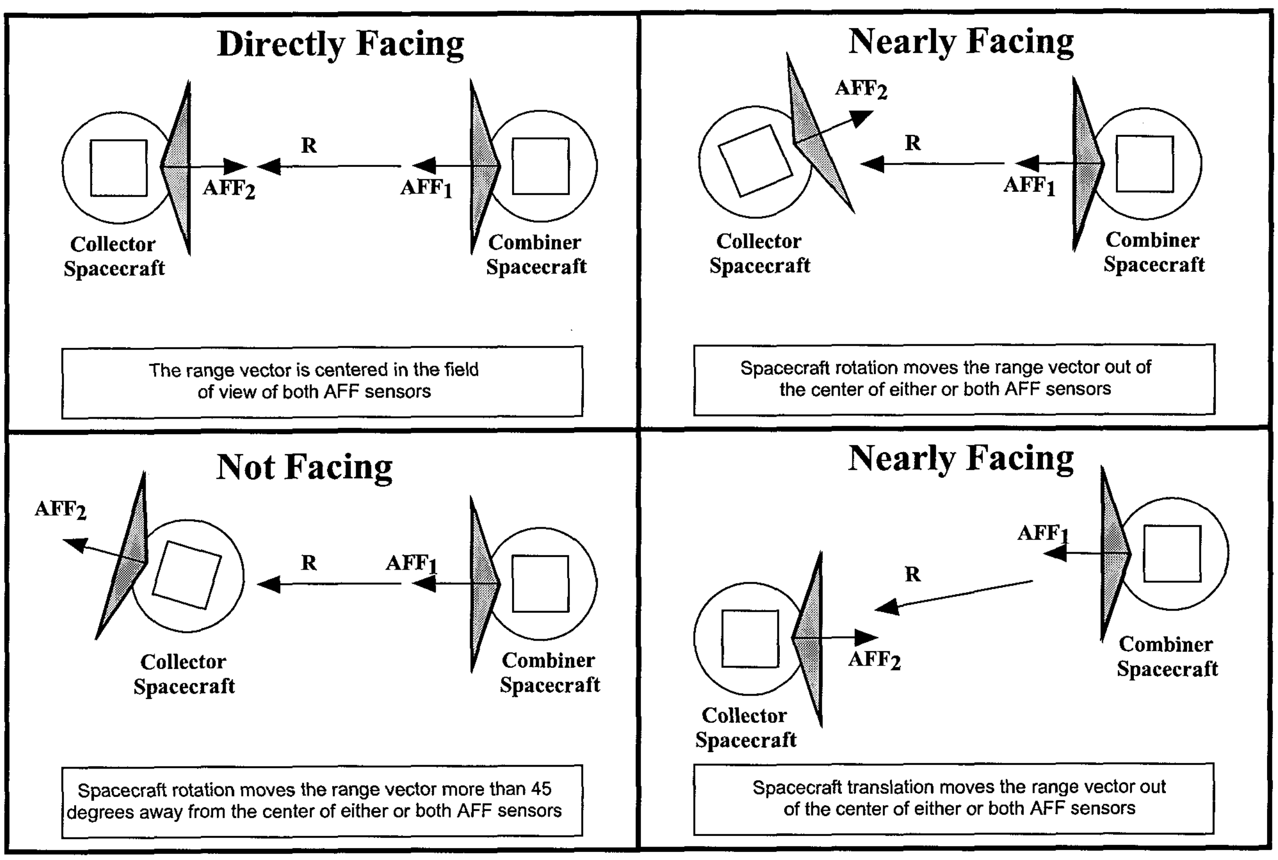

Figure 9. StarLight Flight System Orientations

Each flight system requirement, and each subsequent allocation to a flight system element, must be clearly identified as applicable to all orientations, or applicable to a particular orientation. For StarLight, all the driving requirements are those that are particular to the directly facing orientation.

Flight System Operating Range

The two spacecraft will be operated and tested at a variety of operating ranges, which have been grouped into four domains for the purpose of requirements specification. These range domains are:

(1) The **normal operating range**, in which the two spacecraft are separated by 30 m to 600 m. This is the operating range for all formation flying and interferometry activities that are required for full mission success. The AFF Sensor, the Interferometer, and the Inter-Spacecraft Communications (ISC) link are all required to provide full performance in this operating range.

(2) The **extended operating range**, in which the two spacecraft are separated by 600 m to 1000 m. This is the desired operating range for additional formation flying demonstrations that are planned for the extended mission. The Interferometer is not required to operate at this range. The AFF Sensor and the ISC are required to provide full performance in this operating range.

(3) The **close recovery range,** in which the two spacecraft are separated by 0 m to 30 m. The two spacecraft quickly transit this range following cluster separation, and should remain outside this range for the rest of the mission. The Interferometer is not required to operate at this range, and the AFF Sensor and the ISC can provide degraded performance in this range. If the two spacecraft enter this range due to an anomaly, autonomous fault protection responses will be expected to return the two spacecraft to the normal operating range.

(4) The **distant recovery range**, in which the two spacecraft are separated by 1000 m to 10,000 m. The two spacecraft should never enter this range during the mission. The Interferometer is not required to operate at this range, and the AFF Sensor and the ISC can provide degraded performance in this range. If the two spacecraft enter this range due to an anomaly, autonomous fault protection responses will be expected to return the two spacecraft to the normal operating range.

Note that the Flight System is not required to provide any particular functionality or performance at ranges beyond 10,000 meters. If the two spacecraft were to somehow become separated by more than 10,000 meters, the MOS would be expected to use ground-based navigation techniques and ground-commanded trajectory correction maneuvers to return the two spacecraft back to the distant recovery range.

Formation Performance Level

Referring back to Section 3, the Flight System's alignment and calibration plan involves several cross-system activities. In particular, the Interferometer requires a certain level of Formation performance in order to support the acquisition of inter-spacecraft starlight and metrology. Since the success of one activity may depend on performance gains from some prerequisite activity, we need a way of clearly describing the level of performance expected from the Formation at each point in time, and the conditions present at the time that performance is expected. These Formation performance levels are:

(1) **Post-launch performance**, which is the post-launch performance of the Formation prior to the completion of any ground-directed alignment and calibration activities.

(2) **Initial coarse performance**, which is the unassisted performance of the Formation after ground-directed calibrations of the AFF Sensor, and prior to the initial acquisition of inter-spacecraft metrology.

(3) **Locally calibrated coarse performance**, which is the unassisted performance of the Formation at other ranges, following the completion of metrology-based calibrations at a nearby range.

(4) **Fully calibrated coarse performance**, which is the unassisted performance of the Formation at all ranges, following the completion of metrology-based calibrations at all ranges.

(5) **Locally calibrated precision performance**, which is the Interferometer-assisted performance of the Formation at other ranges, following the completion of metrology-based calibrations at a given range.

(6) **Fully calibrated precision performance**, which is the Interferometer-assisted performance of the Formation at all ranges, following the completion of metrology-based calibrations at all ranges.

Section 6 provides a few detailed examples of the requirements produced by this analysis process. As a concluding comment, it is important to note that although certain permutations of these dimensions are not valid (e.g. fully calibrated performance in the cluster configuration), the number of valid permutations is quite large. For instance, all three operational modes are valid for all three of the ground test configurations. In the separated configuration, all three orientations are valid for all three operational ranges and all four levels of performance.

5. Flight System Requirements Organization

During flight system requirements development, flight system implementation, and flight system verification, different requirements users will want to be able to read, write and modify different requirements subsets. Therefore the flight system requirements should be organized in a manner that supports the varied needs of these different users. A requirements database is a natural choice, and indeed the StarLight flight system requirements, along with all other StarLight project requirements, have been organized using the Dynamic Object-Oriented Requirements System (DOORS), a commercial database package that is well-suited to large, complex systems. However, the best database capabilities in the world can (and have been) defeated by improper organization, administration, and usage. This section will describe some of the approaches that we have employed in establishing a draft set of requirements for our multi-spacecraft flight system. The subsequent sub-sections will cover:

- Requirements Document Organization and Ownership
- Separation of Requirements and Allocations
- Repetition of Requirements as Allocations
- Organization of Requirements
- Organization of Allocations
- Separation of Hardware and Software Requirements

Requirements Document Organization and Ownership

As shown in Figure 10, the StarLight Flight System requirements are organized into three database modules (traditionally referred to as "documents"), each with a different owner. A single master document, appropriately named the Flight System Requirements Document (FSRD), is owned by the flight system's chief engineer. The FSRD responds directly to the Project-level requirements, derives additional Flight System requirements, and sub-allocates Flight System functional and resource requirements to the three flight system elements.

The FSRD directs all of the high-level interferometry performance requirements to the Interferometry Performance Model (IPM), an auxiliary document that is owned by the flight system's interferometry architect. The IPM decomposes the high-level interferometry performance requirements into appropriate allocations for the Interferometer and the Formation. Allocations to the Formation go back to the FSRD as appropriately phrased formation flying requirements. Examples of IPM performance budgets include:

- Siderostat Range of Motion
- Right Arm Starlight Pointing Knowledge
- Inter-Spacecraft Metrology Pointing Knowledge
- Optical Path Delay Knowledge
- Optical Path Delay Rate Knowledge
- Photon Throughput
- Fringe Visibility

The FSRD directs all of the high-level formation flying performance requirements to the Formation Flying Performance Model (FFPM), an auxiliary document that is owned by the flight system's formation flying architect. The FFPM decomposes the high-level formation flying performance requirements (including those derived by the IPM) into appropriate allocations for the three flight system elements. Examples of FFPM performance budgets include:

- Range Knowledge and Control
- Range Rate Knowledge and Control
- Bearing Knowledge and Control
- Bearing Rate Knowledge and Control
- Interferometer Pointing Knowledge and Control
- Quiet Time Between Thruster Firings

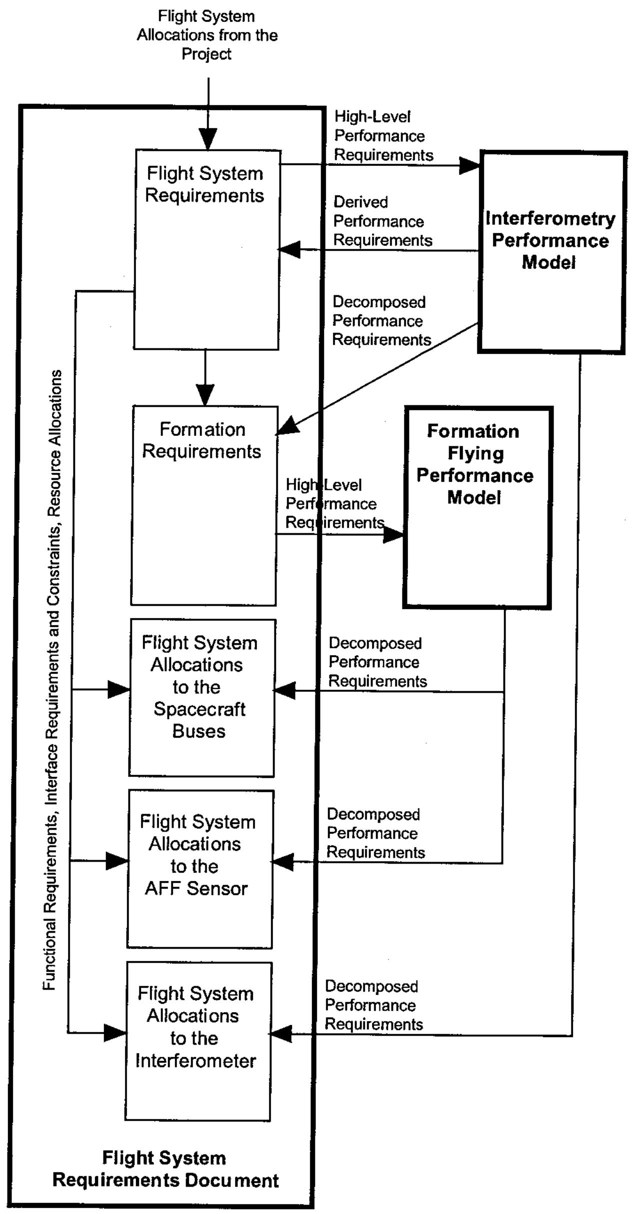

Figure 10. StarLight Flight System Requirements Documents

It is important to note that the FSRD retains a complete set of its output requirements to the IPM and the FFPM, as well as a complete set of its input requirements back from the IPM and the FFPM. So although the IPM and the FFPM are clearly essential to the flight system requirements flowdown, the FSRD retains a complete set of all the flight system requirements and all the flight system allocations. In fact, after the flight system requirements are finalized, the IPM and FFPM could theoretically be deleted without any loss to the flight system specification (however, we certainly plan to retain these performance models, both to improve traceability on this project, and to re-use them on future projects).

Separation of Requirements and Allocations

As the master document for Flight System requirements, the FSRD creates clear distinctions between the Flight System requirements and the Flight System allocations to the flight system elements. Flight System requirements are co-located in a single section of the FSRD. These requirements consistently employ the phrase "The Flight System shall ....", indicating that these requirements are to be verified by the fully integrated Flight System.

Formation requirements are co-located in their own dedicated section of the FSRD. These requirements consistently employ the phrase "The Formation shall .....", indicating that these requirements are to be verified after the integration of the Spacecraft Buses and the AFF Sensor, prior to their integration with the Interferometer.

Flight System allocations to the Spacecraft Buses are co-located in their own dedicated section of the FSRD. These requirements consistently employ phrases such as "Each Spacecraft Bus shall..." and "The Combiner Spacecraft Bus shall ....", which clearly provide a sub-element assignment, and indicate that verification is expected during Spacecraft Bus testing, prior to its integration with the rest of the Flight System.

Flight System allocations to the AFF Sensor are co-located in their own dedicated section of the FSRD. These requirements consistently employ phrases such as "The AFF Sensor shall..." and "Each AFF sub-element shall ....", which clearly provide a sub-element assignment, and indicate that verification is expected during AFF Sensor testing, prior to its integration with the rest of the Flight System.

Flight System allocations to the Interferometer are co-located in their own dedicated section of the FSRD. These requirements consistently employ phrases such as "The Interferometer System shall..." and "The Combiner Interferometer shall ....", which clearly provide a sub-element assignment, and indicate that verification is expected during Interferometer testing, prior to its integration with the rest of the Flight System.

Repetition of Requirements as Allocations

As we just described above, the FSRD strives to capture a complete list of all the requirements that are to be verified at each level of Flight System integration. In support of that objective, the FSRD hosts a lot of Flight System requirements that are later repeated almost verbatim as allocations to one or more of the flight system elements. Section 6 of this paper provides several examples of this repetition. Although this approach tends to increase the raw count of requirements, we believe our requirements database is very capable of appropriately managing this volume, and the resulting completeness and clarity of each FSRD section is well worth the overhead.

Organization of Requirements

In order to encourage a complete elaboration of all the Flight System requirements across all the previously described requirements dimensions, the FSRD organizes the Flight System requirements from a mission planning perspective. The Level 1 outline for FSRD Section 5, which is the section containing these requirements, steps through the flight system configurations in a roughly chronological sequence:

5.1 Requirements Common to All Configurations
5.2 Unstacked Ground Configuration Requirements
5.3 Stacked Ground Configuration Requirements
5.4 Pre-Launch Configuration Requirements
5.5 Launch Configuration Requirements
5.6 Cluster Configuration Requirements
5.7 Separated Configuration Requirements

Note that Section 5.1 allows us to avoid the repetition of requirements that are common to all configurations, but cannot host requirements that are common to several (but not all) configurations.

The Level 2 outline for each Section 5 sub-section is:

5.X.1 Processes and Standards
5.X.2 Mission Requirements
5.X.3 Constraints
5.X.4 Core Services Requirements
5.X.5 Requirements for Engineering Activities
5.X.6 Requirements for Formation Flying Activities
5.X.7 Requirements for Interferometry Activities

where X = 1 to 7, for each of the above-listed flight system configurations. At this level, the first four sub-sections tend to contain requirements that are common to all the planned activities for a given configuration, whereas the last three sub-sections tend to contain requirements that are motivated by specific activities that are planned for that configuration. Most of the items in the Level 2 outline require little if any further organizational decomposition. One exception is the Core Services Requirements, which are organized according to the following Level 3 outline:

5.X.4.1	Initialization
5.X.4.2	Flight-Ground Communications
5.X.4.3	Inter-Spacecraft Communications
5.X.4.4	Uplink Data Processing
5.X.4.5	Downlink Data Processing
5.X.4.6	Timekeeping
5.X.4.7	Planning and Sequencing
5.X.4.8	Autonomy
5.X.4.9	Fault Protection
5.X.4.10	Operability

Note that many of these core services are needed in all flight system configurations, and thus many of these requirements can be stated as common requirements in Section 5.1.

Organization of Allocations

Having used FSRD Section 5 to elaborate the Flight System requirements from a mission plan perspective, the allocations of these requirements are then placed in an outline that can be more coherently interpreted by their recipients, the flight system elements. Allocations for particular configurations, operational modes, and/or semi-systems are grouped together by functional area with other allocations that are common to all configurations, all operational modes, etc. For example, the Level 1 outline of the flight system allocations to the AFF Sensor is as follows:

7	Flight System Allocations to the AFF Sensor
7.1	Processes and Standards
7.2	Mission Requirements
7.3	Constraints
7.4	Initialization
7.5	Flight-Ground Communications
7.6	Inter-Spacecraft Communications
7.7	Command Processing
7.8	Telemetry Processing
7.9	Operational Data Processing
7.10	Task Scheduling
7.11	Timekeeping
7.12	Planning and Sequencing
7.13	Autonomy
7.14	Fault Protection
7.15	Operability
7.16	Measurement Accuracy and Stability
7.17	Checkout and Calibration

Note that the first 15 sub-sections are a flattened version of the Level 2/3 outline for the Flight System requirements. The last two sub-sections contain the performance requirements that are driven by the activity-dependent FSRD requirements, and/or the performance sub-allocations that come directly from the FFPM.

Separation of Hardware and Software Requirements

Each of the flight system elements has flight hardware and flight software, but the FSRD purposely does not attempt to decompose its requirements or its allocations between flight hardware and flight software. The FSRD simply identifies the required capabilities and constraints, the required levels of performance, and the appropriate sub-element assignments. We believe that further decomposition of these requirements between flight hardware and flight software is best left to the system engineers within each flight system element.

6. REQUIREMENTS FLOWDOWN EXAMPLES

StarLight's flight system requirements are still in development. At the time of this writing, the StarLight Project is still in formulation phase, approximately 16 months from its Preliminary Design Review (PDR). However, the following draft requirements are provided as early examples of the above-described approach to our flight system requirements analysis and organization. These requirements are organized into four flowdown examples, which were chosen specifically because they were tractable and illustrative of the relevant concepts. We do not claim that these examples are particularly complicated or technically challenging.

Flowdown Example 1

This example illustrates the straightforward flowdown of a project-level functional requirement to a single flight system element. The FSRD allocates this requirement directly to the Spacecraft Buses, without involving the IPM or the FFPM. In allocating this requirement, the FSRD provides additional elaboration of the project requirement, by identifying the configurations and sub-elements for which this requirement applies.

Project Allocation to the Flight System (PPRD):
"The Flight System shall be able to autonomously limit the magnitude of its angular momentum vector."

Flight System Requirement (FSRD):
"In its cluster configuration, the Flight System shall be able to autonomously limit the magnitude of its angular momentum vector."

Flight System Requirement (FSRD):
"In its separated configuration, the Flight System shall be able to autonomously limit the magnitude of its angular momentum vector."

Flight System Allocation to the Spacecraft Buses (FSRD):
"In the cluster configuration, at least one of the two Spacecraft Buses shall be able to autonomously limit the magnitude of the cluster's angular momentum vector."

Flight System Allocation to the Spacecraft Buses (FSRD):
"In the separated configuration, each Spacecraft Bus shall be able to autonomously limit the magnitude of the spacecraft's angular momentum vector."

Flowdown Example 2

This example illustrates the straightforward flowdown of a launch vehicle interface requirement. The FSRD allocates this requirement directly to each flight system element, without involving the IPM or the FFPM. In allocating this requirement, the FSRD provides additional elaboration of the project requirement, by identifying the configurations and sub-elements for which this requirement applies, and translating the requirement into flight system coordinates.

Project Allocation to the Flight System (PPRD):
"The Flight System shall tolerate a maximum launch vehicle roll rate of 8.06 rad/sec (77 rpm) during ascent."

Flight System Requirement (FSRD):
"In its launch configuration, the Flight System shall tolerate a maximum angular rate of 8.06 rad/sec (77 rpm) about the Flight System's X-axis."

Flight System Allocation to the Spacecraft Buses (FSRD):
"In the launch configuration, each Spacecraft Bus shall tolerate a maximum angular rate of 8.06 rad/sec (77 rpm) about the Flight System's X-axis."

Flight System Allocation to the AFF Sensor (FSRD):
"In the launch configuration, each AFF sub-element shall tolerate a maximum angular rate of 8.06 rad/sec (77 rpm) about the Flight System's X-axis."

Flight System Allocation to the Interferometer (FSRD):
"In the launch configuration, each Interferometer sub-element shall tolerate a maximum angular rate of 8.06 rad/sec (77 rpm) about the Flight System's X-axis."

Flowdown Example 3

This example illustrates the expansion of a simple margin guideline into a series of consistent performance requirements that span all three flight system elements. The FSRD introduces an appropriate level of design margin on top of the project-provided operational margin, and then interfaces with both the IPM and the FFPM during this process. The IPM develops an acquisition pointing budget that is consistent with a required field of regard for the Interferometer. The FFPM decomposes its allocated terms from the IPM's acquisition pointing budget, into knowledge and control requirements for the AFF Sensor and the Spacecraft Buses.

Project Guideline to Flight System (PPRD):
"The Flight System should have 20% operating margin on mechanism range of travel."

Flight System Requirement (FSRD):
"The Flight System shall have 20% operating margin on mechanism range of travel."

Flight System Requirement (FSRD):
"Prior to PDR, the Flight System shall have 30% design margin on mechanism range of travel."

Flight System Requirement (IPM):
"In separated configuration, the flight system shall accommodate a search pattern for intermediate right starlight acquisition of +/- 4.5 arcmin on the collector siderostat." (Further implications of this requirement on collector boresight pointing knowledge will not be discussed)

Formation Requirement (IPM):
"In separated configuration, the collector Spacecraft Bus shall have attitude control accuracy, each axis, during instrument acquisition mode, of less than:

±3 arcmin (40 m separation)
±3 arcmin (600 m separation)"

Formation Requirement (IPM):
"In separated configuration, the Formation shall have formation bearing angle control accuracy, each axis, during instrument acquisition mode, of less than:

±4 arcmin (40 m separation)
±4 arcmin (600 m separation)"

Flight System Allocation to the Interferometer (IPM):
"The instrument system shall provide an optical beam steering range of at least ±23 arcmin for the collector siderostat."

Flight System Allocation to the Spacecraft Buses (FFPM):
"In separated configuration, the two Spacecraft Buses shall use formation bearing angle deadbands, each axis, during instrument acquisition mode, of less than:

±3 arcmin (40 m separation)
±3 arcmin (600 m separation)"

Flight System Allocation to the AFF Sensor (FFPM):
"In separated configuration, the AFF Sensor shall provide formation bearing angle knowledge, each axis, during instrument acquisition mode, of less than:

±1 arcmin (40 m separation)
±1 arcmin (600 m separation)"

Flowdown Example 4

This example illustrates the expansion of a simple margin guideline into a set of consistent resource allocations that spans all three flight system elements. In this case, the shared resource is the Inter-Spacecraft Communications (ISC) bandwidth, which must be divided between several types of information services. The FSRD develops a set of sub-allocations that is consistent with the required ISC capacity and the operational margin guideline, holding back an additional 5% of the capacity as design phase reserve that can be allocated later if necessary.

Project Guideline to the Flight System (PPRD):
"The Flight System should have 20% operating margin for inter-spacecraft data communications."

Flight System Requirement (FSRD):
"The Flight System shall have 20% operational bit rate margin for inter-spacecraft data communications."

Flight System Allocation to the Spacecraft Buses (FSRD):
"The two Spacecraft Buses shall provide an ISC bit rate of 512 kbps in the return direction (Collector to Combiner)."

Flight System Allocation to the Spacecraft Buses (FSRD):
"The two Spacecraft Buses shall provide an ISC bit rate of 512 kbps in the forward direction (Combiner to Collector)."

Flight System Allocation to the Spacecraft Buses (FSRD):
"The Collector Spacecraft Bus shall limit its utilization of the ISC bandwidth in the return direction as follows:
Collector-to-Combiner Commands <= 2 kbps
Collector-to-Combiner Uplink Messages <= 2 kbps
Collector Bus Operational Data <= 2 kbps
Collector Bus Telemetry <= 8 kbps"

(There is a similar allocation for the forward direction)

Flight System Allocation to the AFF Sensor (FSRD):
"The Collector AFF Sensor shall limit its utilization of the ISC bandwidth in the return direction as follows:
Collector AFF Telemetry <= 8 kbps
Collector AFF Operational Data <= 1 kbps"

(There is a similar allocation for the forward direction)

Flight System Allocation to the Interferometer (FSRD):
"The Collector Interferometer shall limit its utilization of the ISC bandwidth in the return direction as follows:
Collector Interferometer Telemetry <= 8 kbps
Collector Interferometer Controls Data <= 353 kbps"

(There is a similar allocation for the forward direction)

7. SUMMARY

The StarLight flight system is composed of two spacecraft, which operate cooperatively with other in order to exercise their distributed payloads. In order to fully specify its flight system requirements, we have developed a requirements analysis framework which incorporates the analysis dimensions that are unique to multi-spacecraft flight systems, namely:

- Flight System Sub-Element
- Flight System Configuration
- Flight System Operational Mode
- Flight System Orientation
- Flight System Operating Range
- Formation Performance Level

We have organized these requirements in a manner that we believe will support the various needs of different users during flight system requirements development, flight system implementation, and flight system verification. We believe our approach can be extended to flight systems with larger collections of cooperating spacecraft.

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